Cinder movement experiments on scoria cones slopes: Rates and direction of transport

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Abstract: As part of a field experiment to examine slope processes, four experimental grids with painted and numbered cinders were placed on the outer crater rims of two scoria cones in the San Francisco volcanic field, Arizona. Each grid contained 50 cinders placed in five rows of ten each. Rows were placed parallel to local slope contours. The mean diameter for each cinder was 1.7±0.2 cm (n = 200) and the average grid slope was 20.2°. Grids were set in July 1992. They were revisited one month later in August 1992 and again two years later in August 1994. Although several cinders failed to show any movement in the August 1992 survey, the average length of movement was 11.2 cm (n = 118). If the total movement is averaged over the 197 cinders that were relocated, the average length of movement then becomes 6.7 cm (n = 197). All cinders showed movement in the August 1994 survey and the average distance of movement was 32.8 cm (n = 141 with 59 missing cinders). The mean annual rate of movement after 25 months was 15.8 cm/yr (n = 141).

Using the convention that the 180° azimuth direction is downslope and perpendicular to local slope contours, the direction of cinder movement more closely approaches 180° with an increase in time. The azimuth directions calculated after just one month of emplacement display greater scatter and variability than the more correlated results measured after 25 months. The mean azimuth value after the 1992 survey was 163.6±54.2° (n = 118), while the mean azimuth after the 1994 survey was 177.9±20.7° (n = 141). Several painted cinders displayed upslope movement when the grids were first visited after one month. However, after two years the cumulative movement for every cinder was downslope from its original position. Non-channel overland flow is interpreted to be the primary erosional agent responsible for moving the cinders in the downhill direction. Rainsplash is interpreted to be responsible for moving the cinders in the upslope direction and is believed to be the major contributor to the variability in the azimuth measurements.

Key words: erosion rates, San Francisco volcanic field, downslope transport, cinder cone, scoria cone, surficial processes, rainsplash, slope wash, overland flow, hillslope processes

Introduction

Most scoria cones (also known as “cinder” cones) are conical structures of ballistically ejected fragments topped by a bowl-shaped crater. These small volcanoes are usually similar in structure and composition and may cluster by the dozens or even hundreds in volcanic fields or on the flanks of larger volcanoes. Youthful cones have a loose and permeable mantle of pyroclastic material, while older cones are characterized by a degraded coneform and an extensive debris apron around the base of the cone. Often the slopes of an older cone will display signs of hydraulic action or overland flow, such as rills or even a more extensive gully network.

A variety of processes can be responsible for eroding a hillslope, including rainsplash, soil creep, freeze-thaw movements, numerous types of mass movements, and running water (slope wash or sheet wash, rilling, and gullying). Scoria cone degradation has been attributed to small debris flows and rilling processes (Dohrenwend et al., 1986; Renault, 1989). Segerstrom (1950, 1960) studied the erosion of the historically active (1943 to 1952) Paricutin scoria cone in Mexico. He noted that rill erosion had not started on the sides of the cone and that the tephra was still too coarse and permeable to permit surface flow of rainwater. He further observed that the ash mantle covering both the cone and surrounding terrain is gradually being removed by raindrop splash, sheet wash, landsliding, channel erosion, and deflation by wind. Wood (1980) cited the importance of weathering on scoria cone slopes and used simple models to quantify cone deg-
The grids were placed on two scoria cones, Black Bottom Crater in the eastern portion of the San Francisco volcanic field and an unnamed cone in the central portion of the field containing Walker Lake (Fig. 1).

**Experimental grids and procedures**

A total of four experimental grids were placed on both the north and south crater rims of Black Bottom Crater (V3901) and the Walker Lake cone (V3611). The grids were emplaced on the north and south rims of each crater and left undisturbed at their initial positions. For example, a grid on the north crater rim has a northern exposure while a grid on the south crater rim has a southern exposure. Each grid contained 50 painted lapilli-size stones (or “cinders”) placed in five rows of ten each with each stone being placed 10 cm from each other. Each grid was placed parallel to the local slope contours, and the position of the cinders was established with reference to wooden stakes at the grid corners. Each stake was approximately 30 cm in length. The long and short axis of each cinder, usually between 1 and 2 cm, was measured to determine the average diameter. The mean diameter for all 200 cinders was 1.7±0.2 cm.

Each experimental cinder was spray-painted white and received an identifying numeral painted in black. The numbering and coordinate systems for each grid were arranged so that the first row of cinders is numbered 1–10 and is upslope from the last row (cinders #41–50). Stake #1 is near cinder #1 and is located at positions 10 cm from each other. Stakes #5 and #10 are at position 110 cm, while stake #3 is at 60 cm from cinder #41 and stake #4 is at 30 cm from cinder #50 (see Figs. 2 and 3). Downslope has been defined as the positive y-axis direction.

In order to record the natural movement of these pyroclastic fragments on the hillslopes, the objective was to choose a site that required little modification or landscaping. Relatively unvegetated sites with bare soil and cinders were selected. Very little vegetation was removed and smoothing or grading of the site was also kept to a minimum. The slope of each grid was measured in three locations with a clipboard and clinometer (pocket transit). Each grid had roughly a 20° average slope. As the cinders were transported downslope beyond the control area of the grid, the slope angle may become more variable, thus creating a potential source of inaccuracy or error.

Grid 1 was placed at an elevation of 6250 ft (1911 m) on the north crater rim (facing north) of Black Bottom Crater. Elevation measurements were made with a hand-held electronic altimeter and checked against the 7.5 minute topographic maps. The surface of the grid has an average slope of 20° dipping to the north (east is the downhill direction at this grid).

The second grid was placed at an elevation of 6240 ft (192 m) on the south rim (facing south) of Black Bottom Crater and slopes 23° to the south (the downhill direction at this grid).

Grid 3 was emplaced on the north crater rim (facing north) of the Walker Lake cone at an elevation of 8400 ft (2585 m). The surface of the grid has an average slope of 19° to the north. This cone is heavily forested, but the grid is located in a clearing from a brush fire (charred logs are common on the cone slopes around this site).

The fourth grid was emplaced at an elevation of 8300 ft (2530 m) on the Walker Lake cone. Because of the difficulty in finding a clearing in the extensive tree growth and the proximity of a dirt trail, this grid was put on the south-southwest slope and therefore faces south-southeast. The average slope for this grid is 19°.

**Results from summer 1992**

The experimental grids were set in July 1992 and revisited roughly 30 days later in August 1992. Although several small thunderstorms occurred during this time, at least one thunderstorm was witnessed at each of the study sites. On-line precipitation records from several local stations also verify July and August rainfall (National Climatic Data Center, see Table 1). Upon revisiting the scoria cones, cinder movement was recorded by tape measure with reference to the corner stakes or pegs. Several cinders showed no movement (no detachment from soil or cinder mantle). A few cinders moved a distance of over 40 cm from their original positions, but the average length of movement was 11.2 cm. The total movement is averaged over all 197 cinders that were relocated, the average length of movement then becomes 6.7 cm (n = 197). The direction of movement was calculated afterwards by using the convention that the 0° azimuth direction is upslope and the 180° azimuth direction is downhill. Upslope and downhill are defined as being perpendicular to the local slope contours or perpendicular to the...
to the rows of cinders. Table 2 summarizes the important statistical information regarding the changes in each grid, while the Appendix lists the position, amount of movement, and direction of movement for each cinder after both field surveys.

After one month, 37 cinders moved from their original positions in grid 1. The remaining experimental stones showed no movement. Although the predominant direction of movement was downhill towards the 180° azimuth, two cinders showed uphill movement. One cinder traveled nearly 80 cm downhill, but the average distance each cinder moved was 15.4 cm ($\bar{x} = 15.4$). Two shallow depressions mark one corner of the grid (Fig. 2a). These depressions were probably created by an animal, but the pattern of displacement was not judged disruptive enough to prevent the use of the recorded measurements (Fig. 3a). It appears that some cinders moved into and along the depressions rather than having been buried or pushed aside. Based upon

### Table 2. Descriptive statistics for changes in the experimental grids

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean distance moved (cm)</td>
<td>15.4</td>
<td>2.1</td>
<td>11.2</td>
</tr>
<tr>
<td>(cm)</td>
<td>31.7°</td>
<td>60°</td>
<td>54.2°</td>
</tr>
<tr>
<td>$\bar{x}$</td>
<td>37</td>
<td>30</td>
<td>118</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>1.7</td>
<td>5.2</td>
<td>4.2</td>
</tr>
</tbody>
</table>

$\bar{x}$ is the number of relocated cinders that showed movement from their original July 1992 positions and $\sigma$ is the standard deviation.

Fig. 2. Selected photographs of the experimental grids. Each cinder was originally placed 10 cm from its neighbor (field rulers and rock hammer for scale).

(a) Grid 1 on August 4, 1992, showing movement of white-painted cinders and two ground depressions across one corner of the grid. The grid is oriented with stake 1 to the left of the photograph. (b) Grid 2 on August 26, 1992, showing 25 months of vertical movement. Grid 1 is at the top of the grid. (c) Grid 3 on August 17, 1994, showing several considerable changes. Downhill is to the top of the photograph.
Field observations of the local area, these grooved disturbances are probably not rills created by hydraulic action.

Thirty cinders had a measurable change in position for the second experimental grid atop Black Bottom Crater. One cinder (38) could not be found, but it can easily be deduced that the cinder was buried because it was found two years later during the 1994 survey. The average distance of movement was 4.5 cm (n = 30). Six cinders showed uphill movement, while three others had movement parallel to the local slope contours (either an azimuth direction of 90° or 270°). No other grid recorded this much movement in an upslope direction (Fig. 4). This movement in an upslope direction is interpreted to be a manifestation of rain splash and will be discussed and analyzed in a later section.

For grid 3, on the northern crater rim of the Walker Lake cone, 46 cinders recorded a change in position after one month. Two cinders showed no movement, while the other two could not be found and presumably were buried, moved an exceptionally large distance downslope, or were removed by an animal. Six cinders, including one that moved in a 90° direction, had an uphill direction of movement. One experimental stone traveled 82.8 cm downslope, the most recorded in this first survey. The average distance of movement was 12.8 cm (n = 46).

Only five cinders moved in grid 4. The average distance of movement was only 3.7 cm (n = 5), the lowest for any grid. No upslope movement was recorded. Since this region of the crater rim is forested, the lack of movement can be attributed to a nearby tree, a Ponderosa Pine (Pinus ponderosa). Located to the northeast of the grid, the trunk of the tree measured 11 ft (3.4 m) from the nearest corner stake of the grid. Although not directly overhead, the branches undoubtedly played a role in sheltering the grid from rain. Some pine needles...
(and an occasional pine cone) are also interspersed amongst the cinder, probably further inhibiting the movements of the marked stones. Additionally, compared to the other grids, this site was emplaced in the coarsest-grained material. Several fragments within and around the grid measured over 3 cm in diameter (Fig. 2d). While the lack of movement within this grid may initially be disappointing, it does indicate that certain factors may inhibit downslope movement of lapilli-size fragments.

Results from summer 1994

The field sites were again visited in August 1994, two years after they were last visited or 25 months since the grids were initially emplaced. All painted cinders now had measurable movement, but over 50 of the original 200 stones could not be found (Fig. 5). In addition to the possibility of being buried, washed downslope beyond the search area, or removed by animals, some experimental cinders may have become unrecognizable due to chipping and removal of the identifying paint. As anticipated, there is now an even more pronounced downslope trend towards the 180° azimuth as the pyroclastic material continues the long-term process of being transported towards the debris aprons around the base of the cone (compare Figs. 4 and 6). The minimum recorded movement was approximately 4 cm by two different cinders, while the maximum recorded movement was 183 cm. As presented in Table 2, the average distance of movement was 25 cm (n = 141).

A few cinders have come to rest against larger pyroclastic fragments or against vegetation. These particles have reached a semi-stable juxtaposition and have at least temporarily halted their downslope movement. Several cinders were found partially buried and a few were found completely buried.

Forty-one cinders were relocated around grid 1 on Black Bottom Crater. As observed at each grid, every cinder now showed movement from its original position. One other cinder (#24) was relocated but discarded from the survey because it was found nestled amongst some rocks (volcanic blocks) and branches over 250 cm and at an azimuth of 233° from its original position. Its ensconced positioning indicates that it was most likely transported or disturbed by an animal. The remaining experimental stones could not be relocated. The average distance each cinder moved from its original position was 26.5 cm (n = 41), an increase from 15.4 cm (n = 37) for those cinders in this grid that had a measurable displacement after the first survey in 1992. Several azimuth measurements greater than 180° in grid 1 suggest the possibility of a slight local tilt in the grid surface towards an angle greater than the 180° azimuth direction (Table 2 and see Figs. 5 and 6). However, this should be viewed in its proper context as each grid has minor surface undulations and other imperfections.

A comparison of Fig. 3a, Fig. 5a, and data provided in the Appendix indicates that while cinder #11 exhibited movement towards the side margin of grid 1, it also displayed an uphill displacement from its position recorded during the August 1992 survey (but it still maintained an overall downslope displacement from its original July 1992 position). This is the only cinder in the August 1994 survey that demonstrated an upslope movement during the two years since the 1992 measurements.

A total of 42 cinders were relocated at grid 2, the second site atop Black Bottom Crater. They had an average displacement or movement distance of 24.6 cm (n = 42). Cinder #37, with its direction of movement being 242°, appears slightly anomalous in context with the rest of the grid and was perhaps disturbed by an animal (Fig. 5b).

Grid 3 experienced significant modifications most likely related to overland flow. The ground surface of the grid itself appears to have been lowered through the loss of material, as suggested by exposed portions of root systems in the surrounding vegetation (mostly grasses), overwashed downslope, including cinders and soil removed from the confines of the experimental grid, has collected against a long log lying 1.5-2 m downhill from the bottom margin of the grid (and slightly diagonal to the margin of the grid) (Fig. 5c). More material has been dislodged and transported downslope at this grid than at any of the others. This area has certainly been subjected to overland flow, perhaps even minor channelized flow in unvegetated sections, and could be the site of an incipient gully.

No painted cinders remained within the confines of grid 3 and only 17 could be found downslope (Fig. 5c). These had an average displacement of 113.8 cm. An extensive search was made for the remaining cinders, especially amongst the sediment deposited against the charred log, but few could be located. Some cinders were beginning to lose their identifying paint and it is possible that the paint chipped and flaked off during transport or weathering. Only one corner stake (#91) was still emplaced; two were lying on the ground and the fourth

![Fig. 5 (a, b, c, d). Plots for each grid illustrating the movement of individual cinders as measured in August 1994 (solid circles). Open circles are the original July 1992 positions. All cinders now show movement after 25 months of emplacement, but many marked cinders could not be located (shown as open circles in their original positions).](image-url)
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Analysis and discussion

Precipitation data recorded during the course of the field experiment are summarized in Table 1. This meteorological station at the Flagstaff airport is one of the closest to both scoria cones and represents the station with the most complete record of precipitation data recorded in 1992–1994, although it had one month with missing or incomplete data. A summary of the data in Table 1 reveals that precipitation amounts in 1992 through 1994 were above the 503 mm mean recorded in 1950 through 1970 by Sellers & Hill (1974).

When the grids were first visited after one month, a small percentage of the painted cinders displayed downward movement from their original July 1992 positions. However, after two years the cumulative movement for every cinder was downslope (Figs. 5 and 6). Overland flow is interpreted to be the primary erosional agent responsible for moving the cinders in the downhill direction perpendicular to the local slope contours (or the rows of cinders). The presence of gullies and rills on the slopes of both selected cones indicates that channelized flow and rilling does occur, but it is less common at the grid sites near the crater rims. The pattern and extensive amount of cinder movement at grid 3 suggests that some channelized overland flow may have developed, but non-channel overland flow appears to be more common. Rainsplash is interpreted to be responsible for moving the cinders in potentially all directions, including upslope.

There are many studies in the literature regarding the various aspects of rainsplash, but two studies will serve to illustrate this process and how it can be identified on scoria cone slopes. Early experiments by Ellison (1944) showed that considerably more soil is splashed downslope than is splashed upslope, producing an asymmetrical pattern of movement. He found that three times as much material was transported downslope than upslope in splashboard experiments on a 6° slope. His experiments also showed that rainsplash transport could cause significant particle movement, including the movement of 0.4 cm stones as far as 20 cm and even smaller particles moving up to 150 cm. Particles moving downslope also traveled greater horizontal distances than those moving upslope. Another experimental study by Mosley (1974) provided data for the relationship between weight of sand splash and distance from source, and slope angle. He demonstrated that 50% of the total weight of the sand was splashed in what would be the downslope direction when the laboratory apparatus was in a horizontal position, but this figure increases to 95% when the sand surface is inclined at an angle of 25°. Both these studies acknowledge that rainfall at an oblique angle adds a further degree of complexity to the process of rainsplash.

Therefore, we can expect those particles that show upslope movement to have traveled a lesser distance than those that show downslope movement. Although it is difficult at best to separate those cinders that have moved by rainsplash from those that have moved by overland flow, and indeed many have certainly moved by a combination of processes, an examination of the cinder movement data from 1992 does appear similar to the results of Ellison (1944) and Mosley (1974). Of the 118 cinders that demonstrated movement after the first month of emplacement, 17 displayed movement in an upslope direction or in a direction parallel to the slope contours (i.e., 90° or 270°). The average movement for cinders moving downslope was 12.4 cm (n = 101), while those moving upslope moved only an average of 3.4 cm (n = 17). If those particles moving in the 90° and 270° directions are switched to the downslope category, the results change slightly with the average downslope movement now being 12.0 cm (n = 106) and upslope movement changing to 3.6 cm (n = 12). Therefore, when using the latter set of calculations, roughly 10% (n = 118) of the cinders showing displacement moved in an upslope direction. When the grids were revisited after two years, the cumulative movement for every cinder was downslope. Upslope transport by rainsplash most assuredly is still occurring, but the overall direction of movement has been downslope from the original positions.

The direction of cinder movement more closely approaches 180° with an increase in time (Fig. 7). The
azimuth measurements calculated after just one month of emplacement display greater scatter and variability than the more correlated results measured after 25 months of emplacement. This is especially evident when comparing the standard deviations (Table 2). Grid 1 is the only grid that has a 1992 mean azimuth value closer to 180° than the 1994 mean azimuth value (this probably reflects a locally tilted grid slope). The mean downslope azimuth value for all cinders after the 1992 survey was 163.6±54.2° (n = 118), while the mean downslope azimuth for all cinders after the 1994 survey was 177.9±20.7° (n = 141). Compared to overland flow processes, rainsplash is believed to be less effective at moving particles directly downslope towards the 180° azimuth. However, it is a greater contributor to the variability of the azimuth measurements.

For calculating the frequency distribution, the histograms reflect a slight bias in recording the movements of the cinders. Surface roughness, non-spherical cinder morphology, and other factors contributed to limiting the accuracy in measuring cinder positions; therefore the measurements were recorded to the nearest half centimeter. Using this approach, cinders that moved directly downslope (i.e., perpendicular to the slope contours) for only a short distance, usually less than 3 cm, were often measured to have a 180° azimuth value. This creates a "clustering" of 180° azimuth measurements. Over a 5 cm distance this causes an uncertainty that approaches 180°±6°, the uncertainty increasing with shorter movement distances. Occurring less frequently, there is a similar bias at 0°, 90°, and 270°. Despite this bias, the results from the 1992 azimuth measurements show greater variability than the results from the 1994 measurements. Although the inaccuracy of the measurements still remains, the cinders had moved greater distances after two years and the bias was no longer present in the data from the 1994 survey.

Additionally, the active surface processes of overland flow and rainsplash were also responsible for an increase in the average distance each painted cinder moved with an increase in time (Table 2 and Fig. 8). The rate at which the painted cinders are moving downslope can also be calculated. Using all 141 cinders relocated in the 1994 survey, the mean annual rate of movement after 25 months was 15.8 cm/yr (Table 3).

### Table 3. Mean rate of cinder movement measured after 25 months (July 1992–August 1994)

<table>
<thead>
<tr>
<th>Grid</th>
<th>Rate of movement (cm/yr)</th>
<th>n²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12.7</td>
<td>41</td>
</tr>
<tr>
<td>2</td>
<td>11.8</td>
<td>42</td>
</tr>
<tr>
<td>3</td>
<td>54.6</td>
<td>17</td>
</tr>
<tr>
<td>4</td>
<td>6.7</td>
<td>41</td>
</tr>
</tbody>
</table>
| 5    | 15.8                     | 141|--

n² is the number of relocated painted cinders after 25 months.

#### Comparison with other research

Only a limited number of researchers have employed the technique of painting stones on hillslopes in order to more fully understand the types and rates of erosional processes. Schumm (1967) monitored the movement of thin, platy fragments of sandstone down hillslopes of Mancos shale near Montrose, western Colorado. After a measurement period that spanned seven years, he determined that the rate of movement of the marked stones was directly proportional to the sine of hillslope inclination. The stones in his study ranged in thickness between 3 to 6 mm, and from 25 to 75 mm in maximum dimension. Although the particle size, lithology, climate, and surficial processes are not directly comparable to this study, Schumm (1967) reported rates of movement ranging from a few millimeters per year on a 3° slope to almost 7 cm/yr on a 40° slope. He concluded that creep induced from frost and freeze-thaw activity was the dominant factor causing downslope transport.

Kirkby & Kirby (1974) painted lines across 12 hillslopes around Tucson in the Sonoran Desert of southern Arizona. Using a 3-month (July–August) study period, they recorded after each rainstorm the movement of painted particles with diameters ≥1 mm. From their field observations and statistical analyses, they concluded that hydraulic action (non-channel overland flow) and rainsplash were the major processes responsible for moving the painted particles. Their statistical results also suggested that the distance moved was directly related to hillslope gradient, inversely related to particle size, and unrelated to distance from the divide.

Recently, Abrahams et al. (1984) analyzed 16 years of painted stone movement on two hillslopes near Barstow in the Mojave Desert, California. They were able to relocate several erosion-monitoring lines established in 1967 by Cooke & Reeves (1972), who only partially completed the interpretation and analysis of this portion of their project. The hillslope profiles examined by Cooke & Reeves were up to 24°, and they measured stones with a minimum diameter of 8 mm. They concluded that hydraulic action rather than creep is the dominant process on these hillslopes. Furthermore, Abrahams et al. noted that the dominance of creep at Schumm’s (1967) Montrose, Colorado, field site could be attributed to the higher altitude and more severe winters of that region.

### Table 4. Comparative rates of stone movement

<table>
<thead>
<tr>
<th>Location and reference</th>
<th>Mean annual precipitation (mm)</th>
<th>Elevation (m)</th>
<th>Slope (degrees)</th>
<th>Stone diameter (mm)</th>
<th>Number of stones</th>
<th>Rate of movement (cm/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Montrose, Colorado</td>
<td>231</td>
<td>2000</td>
<td>20</td>
<td>0.3–7.5</td>
<td>3</td>
<td>1.9</td>
</tr>
<tr>
<td>(Schumm, 1967)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barstow, California</td>
<td>100–200</td>
<td>730–900</td>
<td>20</td>
<td>–</td>
<td>4</td>
<td>0.94</td>
</tr>
<tr>
<td>(Abrahams et al., 1984)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1–2</td>
<td>8</td>
</tr>
<tr>
<td>Flagstaff, Arizona</td>
<td>503</td>
<td>2135</td>
<td>20</td>
<td>1–2</td>
<td>141</td>
<td>15.8</td>
</tr>
<tr>
<td>(This study)</td>
<td></td>
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Field observations and statistical analysis identified two major processes responsible for downslope transport of the painted cinders, non-channel overland flow and rainsplash. Channelized flow or rilling may occasionally occur at one of the four experimental grids. Soil creep (and/or solifluction) and frost heave (freeze-thaw movements) could not be identified with certainty, but they may have also contributed to particle movement (although their contribution is considered to be minimal). Non-channel overland flow (and channelized flow when present) is interpreted to be the primary erosional agent responsible for moving the cinders in the downhill direction (180° azimuth). Rainsplash is believed to be a greater contributor to the variability of the azimuth measurements, including the upslope movement of cinders. When the grids were first visited after one month, 12 of the nearly 200 painted cinders displayed upslope movement (5 others moved parallel to the slope contours). However, after two years the cumulative movement for every relocated cinder was downslope from its original position at the beginning of the experiment. Cinders with an upslope azimuth also moved a shorter distance, generally only 25–33% as much as those with downslope movement.

Carson & Kirby (1972, p. 189) state that "rain-splash can directly move debris of up to at least 1.0 cm diameter and indirectly it can move much larger stones". This study identified rainsplash transport in an upslope direction for cinders with a mean diameter between 1–2 cm. The upslope movement of these pyroclasts was probably facilitated by their vesicular nature and consequent low specific gravity.

Although the grids were emplaced on both north and south rims of two different scoria cones and each cone had a different crater rim elevation, microclimate effects could not be confidently identified from any of the analyses. A more extensive network of grids and a longer monitoring period may be needed before microclimatic effects can be determined. Although not directly overhead, the branches of a Ponderosa Pine undoubtedly played a role in sheltering one grid from rain and thereby offers at least a partial...
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Morphological and geological evidence for glaciotectonics in the area of the Saalian Glaciation, with special reference to Middle Poland

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Abstract: The definition of glaciotectonics to include both the effects of glaciodynamic processes and the effects of glacioisostatic processes has been generally accepted. In Poland, the glaciotectonic style of the Wartanian zone is one of the most distinctive features of the Saalian area; glaciotectonic symptoms are numerous in the western part, but disappear in the east. Such a division extends beyond the Polish borders – as continuous thrust ridges in the west and as a sporadic phenomenon in the east. Attention is drawn to the relationships between geological structure and morphological features; they include such cases as: direct reflection of thrusts in convex land forms, low-relief areas and relief inversion (in relation to the structure). Much importance has been attached to the marginal zone of the Lodz Plateau in Middle Poland. This paper reviews the main genetic hypotheses which, usually, are based on the mechanism, rather than palaeogeographical conditions. Despite much discussion, several problems remain, e.g.: why, allowing that the mechanism was similar, there are such regional differences; why are the marginal zone of the Warta Stadal and the western part of Europe so well endowed in this respect; could palaeoecological conditions (different patterns of glaciation and deglaciation), and postglacial vertical compensatory movements have conditioned the regional variation?

Key words: glaciotectonics, relief, Saalian glaciation, Middle Poland

The extent of the terms

Glaciotectonics, the term relating to processes and phenomena associated with the action of an ice sheet on its bedrock, is not always defined in the same way. Differences involve the acceptance or elimination of certain effects of that action, e.g. deformation structures which result from dead ice pressure. Contrary definitions may be cited as an example. Barkowski (1968, 1974) proposed the term "glaciotectonics" in respect of "all disturbances of the structure of ice sheet material and its bedrock caused by dynamic pressure", where the term "dynamic pressure" is defined as "tangential pressure as a resultant of vertical stress of the ice mass and the horizontal "dynamic" movement of moving ice mass". Therefore, all diapirc effects, especially in dead ice conditions, cannot be glaciotectonic, as this author clearly points out (Barkowski, 1974, p. 25). Jaroszewski (1985, p. 81) gave a radically different definition, according to which "glaciotectonic" is "deformation of ice sheet bedrock and material resulting from ice pressure and/or its friction with the bedrock". A similar opinion is expressed by Ruszczyńska-Szczepaniak (1983), who regards "glaciotectonics" as "the mechanical action of an ice sheet on the bedrock". The author of the present work favours the view of Jaroszewski and Ruszczyńska-Szczepaniak. Thus, any further consideration of "glaciotectonics" in this paper will be based on their definitions, and the effects of differential ice pressure, such as diapirc movement of susceptible material in coarse-grained kame deposits. The latter are very often omitted from similar studies, but will be included in the present discussions.

By "the Saalian zone" (including the glaciotectonic section), the author means "the area in which glacial deposits of that age create the youngest Pleistocene member of a surface geological structure". This zone is E-W oriented, though gently deflected to the NE, and does not remain consistent in width – several deep salients reach far to the south. The deepest of these indicates the presence of the Saalian ice sheet at the Moravian Gate, while shallower ones occur along the Vistula valley as far as the San River mouth and in the Nida Basin. As a generalisation, one might agree that